Relationship of acoustic emission during radial compression to mass loss from decay

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Abstract

White fir specimens decayed by a brown-rot fungus, *Poria placenta,* with mass losses of 1.3, 13, and 28 percent, were tested for radial compressive strength. The 10 by 10 by 20 (radial) mm specimens were compressed at 0.5 mm/min., while acoustic emission (AE) was measured using a 175 kHz sensor at 90 dB gain and 0.7 volt threshold. AE events increased substantially with degree of decay, including specimens with only 1.3 percent mass loss. Several analysis techniques produced high correlations of the data, including stress at a selected AE event level, events per unit stress versus mass loss, and events at a selected compression level. The AE technique appears to be both a sensitive and absolute measure of degree of degradation.

The earliest stage of decay detectable by either microscopy or with the "pick test" is at about 5 to 10 percent mass loss (11, 12). Toughness is considered the strength property most sensitive to decay, with up to 50 percent strength loss at 1 percent mass loss from decay (6). Since most of the wood strength is lost in the early stages of decay, a simple and accurate detection method is needed in both the laboratory and the field. Radial compressive strength (RCS) has been shown to be a sensitive indicator of wood decay (8-10). The initial study of RCS and decay was reported by Toole (9) for southern pine decayed by a brown-rot fungus, *Poria placenta.* After decay, the 20-mm cubes were soaked (to minimize crumbling) and compressed radially at 0.25 mm/min. The reductions in MOE, FSPL, and RCS at 5 percent compression were all highly correlated with 0.3 to 17 percent mass loss. In an expanded study, Toole (10) exposed three wood species (southern pine, sweetgum, and sugar hackberry) to seven different brown- and white-rot fungi, using the same procedures. RCS at 5 percent compression provided the highest correlation of the strength parameters with mass loss from decay, with R^2 from 86 to 94 percent. Smith and Graham (8) exposed Douglas-fir to *Poria placenta,* with mass losses up to about 20 percent. Test specimens were prepared as 10-mm-diameter plugs, 20 mm long (radially), and conditioned to 13 percent equilibrium moisture content (EMC) prior to testing at 0.3 mm/min. RCS at 5 percent compression was highly correlated with mass loss, in agreement with Toole (10). The RCS loss was evident at less than 1 percent mass loss and generally before microscopic confirmation of decay. The initial compressive failure was proposed to have been in the weakest earlywood layer.

Noguchi (4) has shown that acoustic emission (AE) during static bending is sensitive to mass loss of western hemlock decayed by a brown-rot fungus. The average mass losses of the 20 by 20 by 320 mm specimens ranged up to 5 percent. In general, sound specimens produced emissions starting about 50 percent of the ultimate load, whereas decayed specimens had initial emissions at about 10 percent. AE counts were measured at 150 kHz, with the sensor mounted on the side of the beam, using a gain of 60 dB and threshold of 0.1 V (sensitivity of 0.1 mV). The AE count versus load curves did not show any particular relationship of AE and degree of mass loss. This might be anticipated because of the decay gradient and nonuniformity of decay on the surface of the beams at such low average mass losses. Noguchi (5) also measured AE activity from brown-rot decayed western hemlock having a range of mass loss from 2.8 to 5.8 percent. The specimens were loaded in compression on either the radial and tangential face, and the AE sensor was mounted on the adjacent face of the specimen. The load head, which was shown schematically, appeared to be similar to the type used in static bending. AE parameters and specimen size were the same as the static bending tests (4). Controls were loaded in only the tangential direction. In
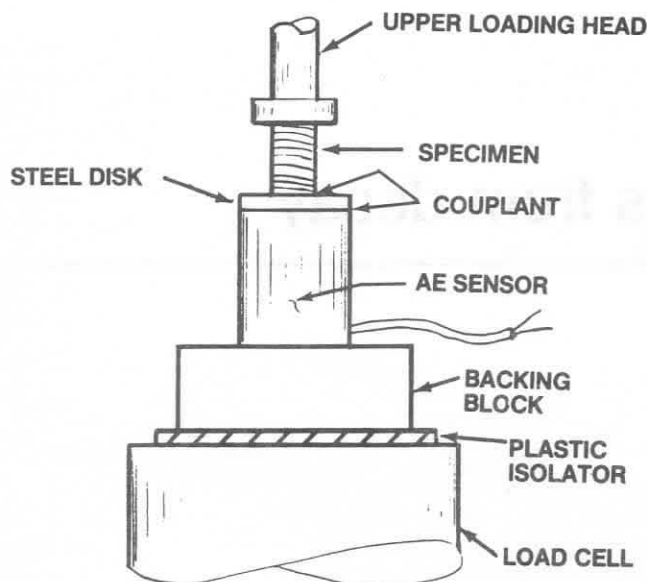
Figure 1. — Arrangement for radial compressive test.

UPPER LOADING HEAD
SPECIMEN
STEEL DISK
COUPLANT
AE SENSOR
BACKING BLOCK
PLASTIC ISOLATOR
LOAD CELL

general, tangential-direction loading produced greater AE than radial loading at the same stress level. Also, decayed specimens produced initial AE at about one-tenth the load of controls. No attempt was made to quantify the interrelationship of AE counts, mass loss from decay, or imposed load.

AE is generated by materials under stress, which emit elastic stress or strain waves (2). Most AE sensing applications use resonant piezoelectric transducers in the ultrasonic range. For wood-base materials, the range of about 100 to 200 kHz provides sufficient sensitivity to emissions of interest, while eliminating background noise from such sources as testing machines (1). One of the most critical factors in AE sensing is the coupling between sensor face and the sensed material, in that air gaps greatly attenuate ultrasonic transmission. An AE event is a "burst type" emission, causing an oscillation of the piezoelectric transducer, which decays somewhat exponentially. The most important AE variables are event rates, total events, and peak amplitude of events. Sensitivity to events is established by the system gain and a threshold level that the event must exceed before detection. Each crossing of the oscillations of an event signal above the threshold level is termed an "AE count," to which older or less sophisticated systems were limited. One of the most important AE observations is the Kaiser Effect, which under cyclic loading, is the absence of emissions until the previous load is exceeded.

The major objectives of this study were to 1) design a test configuration enabling AE events to be sensed without substantial acoustical interference, and 2) determine the relationship of AE parameters to RCS and mass loss. A small number of specimens (and replicates) were selected from previously decayed material to determine if the AE approach showed promise.

Experimental procedure

Blocks of white fir [*Abies concolor* (Gord. & Glend.) Lindl.] were decayed by *Poria placenta* (Fr.) Cke. using a soil-block procedure according to ASTM D2017-81, except with the soil wetted to 160 percent of the moisture-holding capacity. After exposure, each test block was cut into two test specimens of nominal dimensions 10 by 10 by 20 mm long (radially) and conditioned at 10 percent EMC. This size was chosen to approximate that used by Smith and Graham (8). Average mass lossses of the blocks were 0 to 28 percent, which were calculated from equilibration values at 12 percent EMC conditions before and after exposure. Although there could have been some error associated with this mass loss calculation, the controls had no mass change between the exposure periods, reducing the likely error. Growth rates ranged from 4 to 7 mm/ring and nominal density was 360 kg/m^3. Compression tests were run on a model TTD Instron at 0.5 mm/min. Figure 1 shows the arrangement of the sensor and specimen. A steel disk was added to prevent deformation of the sensor face. The upper loading head and sensor were acoustically isolated from the testing machine. A fluorocarbon couplant was applied to the bottom of the specimen in contact with the steel disk. The AE system (AET 5000) was operated at 90 dB gain and 0.7 V threshold (sensitivity of 22 µV), with a 175 kHz resonant sensor and preamp filter bandpass of 125 to 250 kHz. The force data were acquired from the load cell (below the sensor) via the AET 5000 analog parameter port, which was sampled at 0.5-sec. intervals. The tests were run to about 8 percent compression of specimens. AE data were recorded to disk and later postprocessed. Preliminary tests were run on Douglas-fir to establish procedures and AE equipment settings.
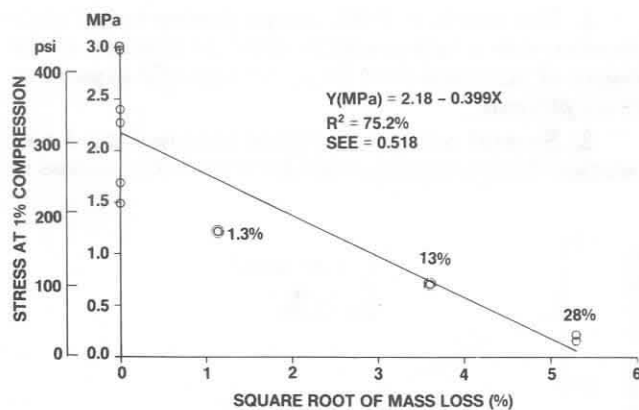
Results and discussion

Preliminary test results on nondecayed Douglas-fir were used to establish sensor positioning, means of coupling to specimens, and acoustic isolation. Tests with cyclical loading confirmed that the material follows the Kaiser Effect and permitted the maximum sensitivity to be established. However, a very high gain was required (100 dB at 0.7 V threshold) to detect events from Douglas-fir. At these settings, only about 50 AE events were detected to 2 to 3 percent compression. The events occurred in groups, possibly related to the initial compressive failure sites in bands of earlywood, as confirmed by Smith and Graham (8). Tests on decayed Douglas-fir specimens showed that mass loss levels as low as 3 percent resulted in AE events that were several orders of magnitude greater than the controls, suggesting that AE may be a sensitive detection method for small levels of decay. When the initial sensitivity setting determined for Douglas-fir was used for white fir controls, more than 10,000 AE events were generated at a similar stress level, requiring a reduction in gain to 90 dB for the main study, and indicating that species variability is a major variable that needs further study.

Table 1 summarizes the specimen characteristics and AE data for the white fir specimens. In analysis of the load-deflection data, it was found that 1 percent RCS values correlated highly ($R^2 > 98\%$) with 5 percent RCS, whereas AE data at 5 percent compression (well beyond the elastic range) correlated poorly. Figure 2, stress at 1

TABLE 1 — Stress and AE data for test specimens.

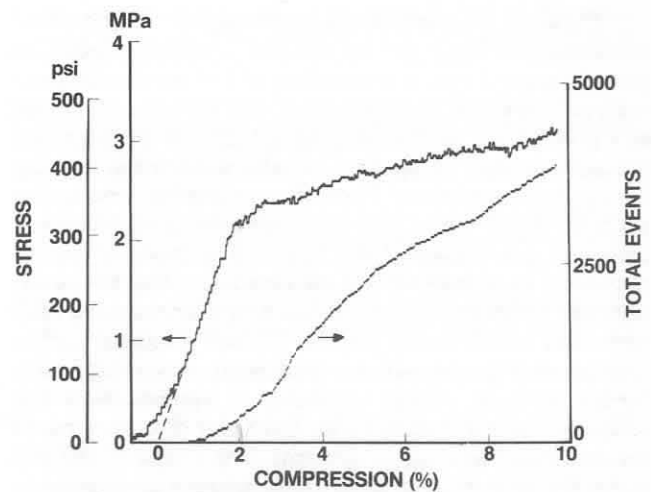| Specimen	Mass loss	Stress at 1% compression	Events at 0.75% compression	Stress at 100 events	Events/ stress to 0.75% compression
	(%)	(MPa)		(MPa)	
C1	0	1.49	3	3.25	0.0027
C2	0	1.69	4	2.97	0.0031
C3a	0	2.98	12	2.99	0.0054
C3b	0	3.03	5	4.45	0.0022
C4a	0	2.27	4	3.50	0.0022
C4b	0	2.40	12	3.29	0.0067
1a	1.3	1.22	44	1.44	0.0478
1b	1.3	1.22	47	1.22	0.0512
13a	13	0.71	257	0.36	0.481
13b	13	0.71	119	0.53	0.223
28a	28	0.22	453	0.13	2.72
28b	28	0.16	1,592	0.08	13.6

Figure 3. — Radial compressive stress and corresponding acoustic emission versus compressive strain for a slightly decayed specimen of white fir (1.3% mass loss).
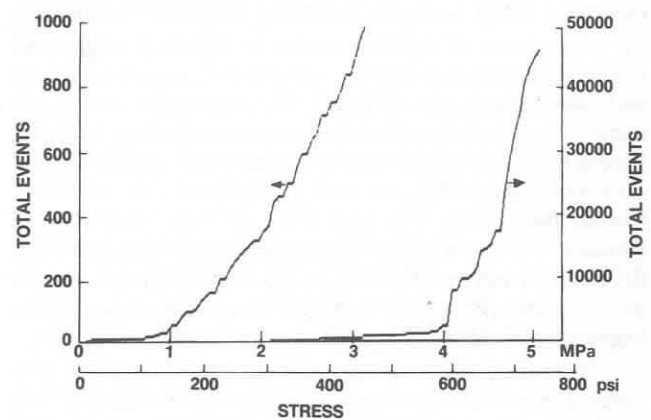

$$Y(MPa) = 2.18 - 0.399X$$
$$R^2 = 75.2\%$$
$$SEE = 0.518$$

Figure 2. — Stress at 1 percent compression during radial compressive test versus degree of mass loss for white fir decayed by *Poria placenta* (6 controls; 6 decayed).

Figure 4. — Acoustic emission output for a white fir control at 100 dB gain.

percent compression versus mass loss, shows the typical relationship previously established (8, 10). The value at 1 percent compression was obtained by extrapolating the linear portion of the load-compression curve to establish zero compression. (An alternative approach, using the initial departure of the load curve, gave similar results.) The relationships in Figure 2 confirmed the general validity of the test procedure and mass loss data. One disadvantage of RCS for predicting the degree of decay is the relative nature of the technique. From Figure 2 and the data in the literature, the range of RCS for control specimens overlaps with those having incipient decay. This potentially limits RCS evaluation to laboratory studies, where controls and replicates are available.

Figure 3 shows typical stress-strain and AE curves for white fir specimen 1a (1.3% mass loss). Note the minor AE activity up to about 2 percent compression (just past the elastic limit). To those unaccustomed to AE data, it may appear to be inconsistent that AE events are detected within the "elastic range." However, these events are caused by very minor defects that generally do not continue to grow if the load is applied cyclically, in accordance with the Kaiser Effect. Slow

rates of AE are also produced in tension testing within the "elastic range" and such AE has been shown to originate from "microcracks" within the cell wall (7). These microcracks originated at bordered pits of tracheids, traveling in the S1 to S3 microfibril direction, but were arrested after a short distance, probably at the point of increased S2 layer thickness.

Figure 4 shows AE events from a white fir control monitored at 100 dB gain. The right curve represents the complete AE event activity to about 5 percent compression; the left is an expansion of the events within the elastic range, to about 1.5 percent compression. Because the 100 dB gain produced event rates that approached the processing limits for the equipment, a reduced gain (90 dB) was used for all other specimens. Although necessary for data acquisition, the reduced gain eliminated some of the available AE data. Since the 1.5 percent compression is within the elastic range, some care must be taken if AE data are used to define the elastic limit, as discussed previously.

Figure 5 is a superposed photocopy of all AE versus stress curves. The 1,000 total event level was selected to provide a good visual separation of the curves. In general, as the mass loss increased, the number of events at a given level increased dramatically. Even with the limited number of specimens, the separation among decay levels was clear. Note the variability among the six controls (C = controls; those with the same letter are from the same original soil block). The mode of failure appeared to relate to the curve shape: the two with abrupt transitions (C1, C3b) had singular crushing failures that were clearly visible, C2 had a barely visible failure, and the remainder had been compressed uniformly without visible crushing. It appears that the shape of the curve may be an indicator of failure mode for compression tests in general. The shape of the AE curve for catastrophic failure in reinforced composites is similar to those of C1 and C3b, since very high rates of emissions are generated at specific damaged sites (3). Specimens 4a and 4b were somewhat different from the other controls, in that they had developed a mold infection. However, their AE curves were not distinguishable from other controls, inferring no cell wall damage.

The shape of the AE curves in Figure 5 suggested that a suitable fixed level of total events might correlate well with mass loss. If valid, this approach would not require measurement of compression during loading. Stress at four levels of total events (1,000, 500, 100, and 50 events) was obtained and regressions run on stress versus mass loss. The best data fit was logarithm of stress at 100 events versus square root of mass loss (Fig. 6). Correlation coefficients at 50 and 100 total events were similar (R^2 = 95.5 and 96.7%) and decreased at the higher levels (500: R^2 = 93.3%; 1,000: R^2 = 91.2%).

An additional means of data analysis was performed. Since one specimen was beyond the elastic limit for 1 percent compression, the number of events was determined at several lower levels, 0.5 and 0.75 percent compression. At 0.5 percent compression, there was

considerable data overlap, however, at 0.75 percent the relationship was substantially improved. Logarithm events at 0.75 percent compression versus square root of mass loss had an R^2 = 90.6 percent. When total events at 0.75 percent compression are divided by the load, the slope within the elastic range is obtained for the relationships of Figure 5. Figure 7 shows an order of magnitude difference in the slope between each succeeding group of specimens, indicating that events per unit stress is an especially sensitive measure of cell wall attack by fungi.

In summary, although there were a limited number of specimens and replicates, the AE data showed substantial differences with degree of mass loss from decay. Additionally, for the variables investigated in this study, the AE technique appears to have both relative and absolute value in assessing the degree of decay.

Conclusions

1. The number of AE events during radial compression was a very sensitive absolute measure of the degree of mass loss from decay for white fir exposed to *Poria placenta*.

2. Several analysis methods produced good correlations between number of AE events and mass loss or

Figure 6. — Logarithm (base 10) of stress at 100 total events versus square root of mass loss (6 controls; 6 decayed).
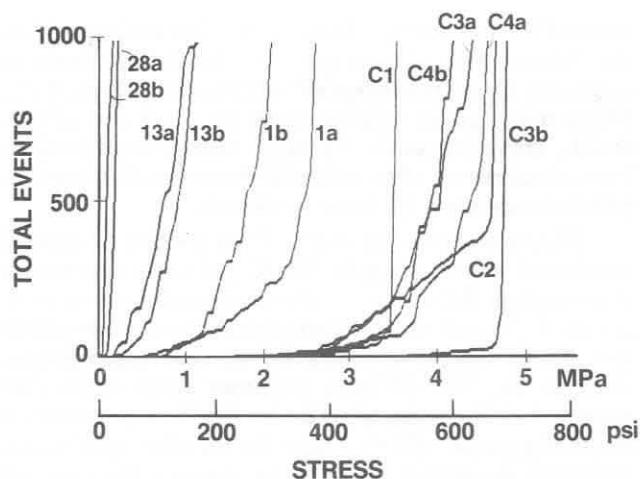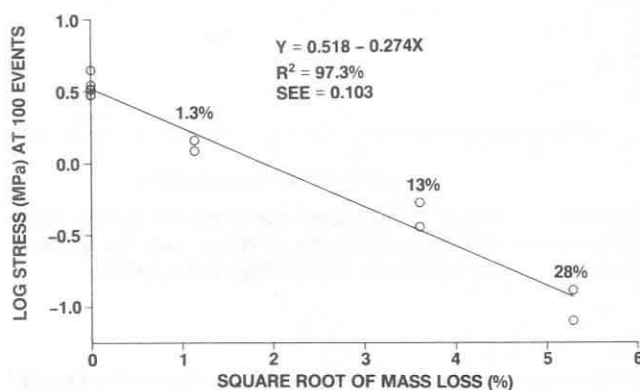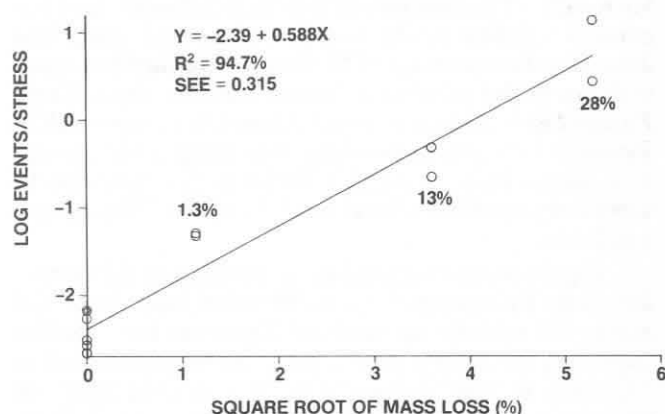
Figure 5. — Acoustic emission versus stress curves for all specimens. Prefixes refer to nominal mass loss (C = control). 1,000 total events were arbitrarily chosen to show differences among results.

Figure 7. — Logarithm (base 10) of events per unit stress to 0.75 percent elastic compression versus square root of mass loss (6 controls: 6 decayed).

stress: stress to produce an arbitrary event total, total events at 0.75 percent elastic compression, and events per unit stress within the elastic range.

3. For nondecayed controls, the mode of failure in compression was related to the shape of the total AE event versus load curves.

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